

Source rock analysis, thermal maturation and hydrocarbon generation using rock-eval pyrolysis in parts of Krishna–Godavari basin, India: a case study

K. Ramachandran · Vinay Babu · Bijaya K. Behera ·
T. Harinarayana

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Abstract Among the various techniques available, the geochemical technique involving total organic carbon content (TOC) and rock-eval pyrolysis are regularly being used in hydrocarbon exploration. They provide information on the kerogen type, sedimentary environment, effective source rock identification and its thermal maturity. In the present study, core samples from three deep boreholes in Krishna–Godavari basin are analyzed to understand the hydrocarbon scenario in parts of the basin. Based on TOC and rock-eval pyrolysis significantly thick, indigenous immature to early mature gas-prone shales from borehole GERMI #1; while non-indigenous, early mature to mature oil and gas-prone shales from borehole GERMI #2 and GERMI #3. Interpreted hydrocarbon typing is supported by well-testing analysis. Break in vitrinite reflectance (R_o) profile is also observed; indicative of significant erosion during Late Cretaceous sedimentation due to tectonic uplift during this time and associated high heat flow causes for thermal maturation of overlying units.

Keywords Source · Rock potential · Rock-eval pyrolysis · Total organic carbon · Krishna–Godavari Basin

Introduction

There are three major sedimentary basins along the east coast of India, namely, the Cauvery, the Krishna–Godavari and Mahanadi. Among three sedimentary basins, Krishna–Godavari (KG) basin located between the major rivers Krishna and the Godavari and also extending offshore, has attracted many oil and gas companies due to its richness in hydrocarbon potential. The location map of exploration block KG-OSN-2001/3 in Krishna–Godavari basin along with the boreholes is shown in Fig. 1. This block comprises an area of 1,850 km² in NE–SW trending Krishna–Godavari (KG) Basin and is located on the eastern coast of the Andhra Pradesh, India (Tidar and Budi 2005). It represents typical divergent passive margin of east coast. It is a proved petroliferous basin (Rai et al. 1998; Biswas 1998) with an aerial extent of 15,000 km² on land and about 25,000 km² of adjoining offshore area up to 1,000 m isobaths line (Kumar 1983). The detailed general geology and tectonics of the basin has already been described (Gupta 2006; Rao 2001). The well-known major Godavari rift extends both onland and offshore. On land, it is exposed near Wardha towards the north western direction and extends to the sea in the south east direction. In the seaward portion, it crosses the shelf and enters the deep sea. The generalized stratigraphy of Krishna–Godavari basin is shown in Fig. 3. It contains the rocks from Cretaceous to Tertiary, different rock types are sand, sandstone, mudstone, shale, clay, siltstone, silt, volcanic and limestone (IHS 2005). The Godavari Graben is filled with a maximum of 2.8-km-thick Early Gondwana (Late Permian to Early Triassic) sediments (Kaila et al. 2005). In between these horst structures, three sub-basins are, namely, Krishna, West Godavari and the East Godavari. The basin is dominated by deltaic plains near the sea–land boundary. From

K. Ramachandran
Petroleum Research Wing, Gujarat Energy Research and
Management Institute, Gandhinagar, Gujarat, India

V. Babu (✉) · B. K. Behera
School of Petroleum Technology, Pandit Deendayal Petroleum
University, Gandhinagar, Gujarat, India
e-mail: vinthegreat84@gmail.com
URL: http://www.spt.pdpu.ac.in/ri_vinaybabu.html

T. Harinarayana
Gujarat Energy Research and Management Institute,
Gandhinagar, Gujarat, India

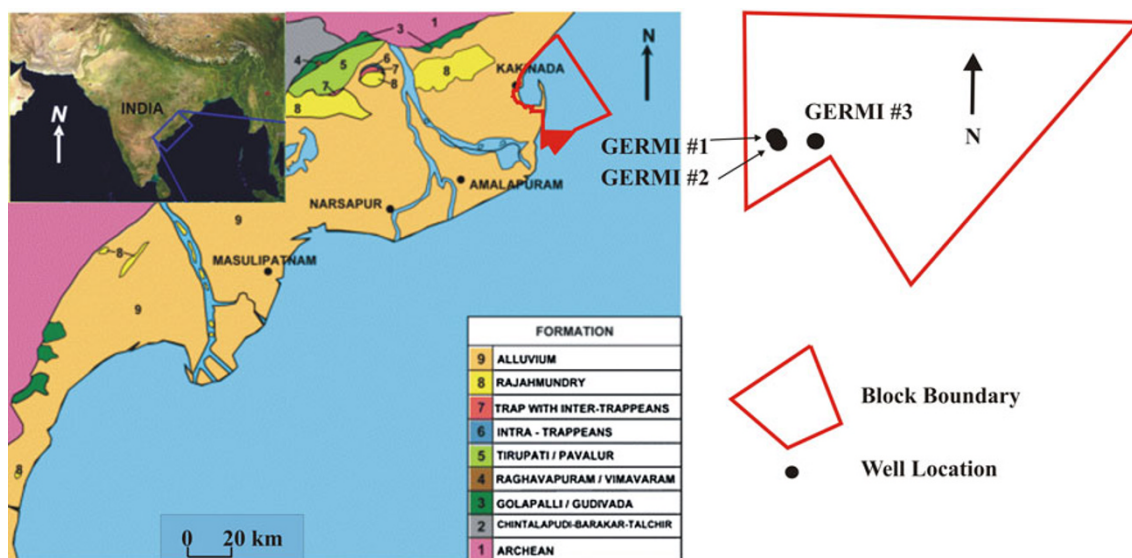


Fig. 1 Simplified geologic map of the area and location of wells (GERMI #1, GERMI #2 and GERMI #3) in Krishna–Godavari basin after (Gupta 2006)

the study of gravity anomalies, three basins have been characterized separated by the two basement horsts namely, Bapatla and Tanuku (Venkatarangan and Ray 1993; Murthy et al. 1995; Subrahmanyam et al. 2008; Murthy et al. 2010). The basin has significant hydrocarbon potential both in the Tertiary delta as well as in the channel–levee–overbank play types in the deepwaters (Saxena et al. 2011).

Three important geological units of KG basin are Northern graben, the central Horst and several sub-basins (Fig. 2). Unlike other basins on the east coast of India, the KG basin is considered to be unique in nature as it is reported that hydrocarbon potential identified in almost all the stratigraphic formations. For example, Triassic Mandapeta formation, Late Jurassic Gollapalli formation, Early Cretaceous Raghavapuram formation, Late Cretaceous Tirupati formation, Eocene Pasarlupudi formation, Eocene–Oligocene–Miocene Matsyapuri formation/Ravva formation and Pliocene Godavari clay formations, all known to be rich in hydrocarbons (Fig. 3). More prominently, the Ravva structure and Godavari formation of Paleocene period are all known to contain significant hydrocarbon potential (Govindan 1984) and thus the basin has emerged as one of the most promising area for exploration. These reservoirs have been charged at different maturity levels of corresponding sources within different stratigraphic sequences (Saxena et al. 2011).

In this region, recently 15 TCF of gas initially in-place (GIIP) and 38,000 barrels oil is proved through exploration drilling process (IHS 2005). Although much of the area on the land has been investigated in detail, the offshore region is relatively poorly investigated due to high cost of drilling in offshore region. In view of this, it is necessary to make a

detailed and careful analysis of the meagerly available data from the offshore boreholes. In view of the above, present study is aimed to make a detailed analysis of a few borehole core samples from three deep offshore wells using the well-known TOC and rock-eval pyrolysis tools.

Sampling and methodology

The data acquired for the present study are mainly related to three offshore deep boreholes of KG basin (Table 1). The appropriate location of the wells namely GERMI #1, GERMI #2 and GERMI #3 are presented in Fig. 4. From these three boreholes, a number of 38 drillcore samples have been subjected to detailed analysis for TOC and rock-eval pyrolysis. Rock-eval pyrolysis study of samples has been carried out in ACS lab (Tidar and Budi 2005). In general, samples with TOC values greater than 0.5 % for shales and 0.3 % for carbonates are considered suitable for rock-eval pyrolysis. Rock samples are pyrolyzed using Rock-Eval 6 apparatus at ACS core laboratory. This technique evaluates oil and gas potential, the generation, thermal maturity and identifies organic matter type (Peters 1986; Tissot and Welte 1978). This instrument uses a ramped temperature pyrolysis technique, whereby a small amount of sample (70–100 mg) is heated in an inert atmosphere (helium or nitrogen) and also combusted with air to obtain several key geochemical parameters relating to the hydrocarbon potential of the rock such as the total organic carbon (TOC), type or quality of organic matter and maturity level (Peters 1986; Lafargue et al. 1998; Behar et al. 2001).

Fig. 2 Tectonic map of Krishna–Godavari basin after (Gupta 2006). All the wells are in western Godavari sub-basin

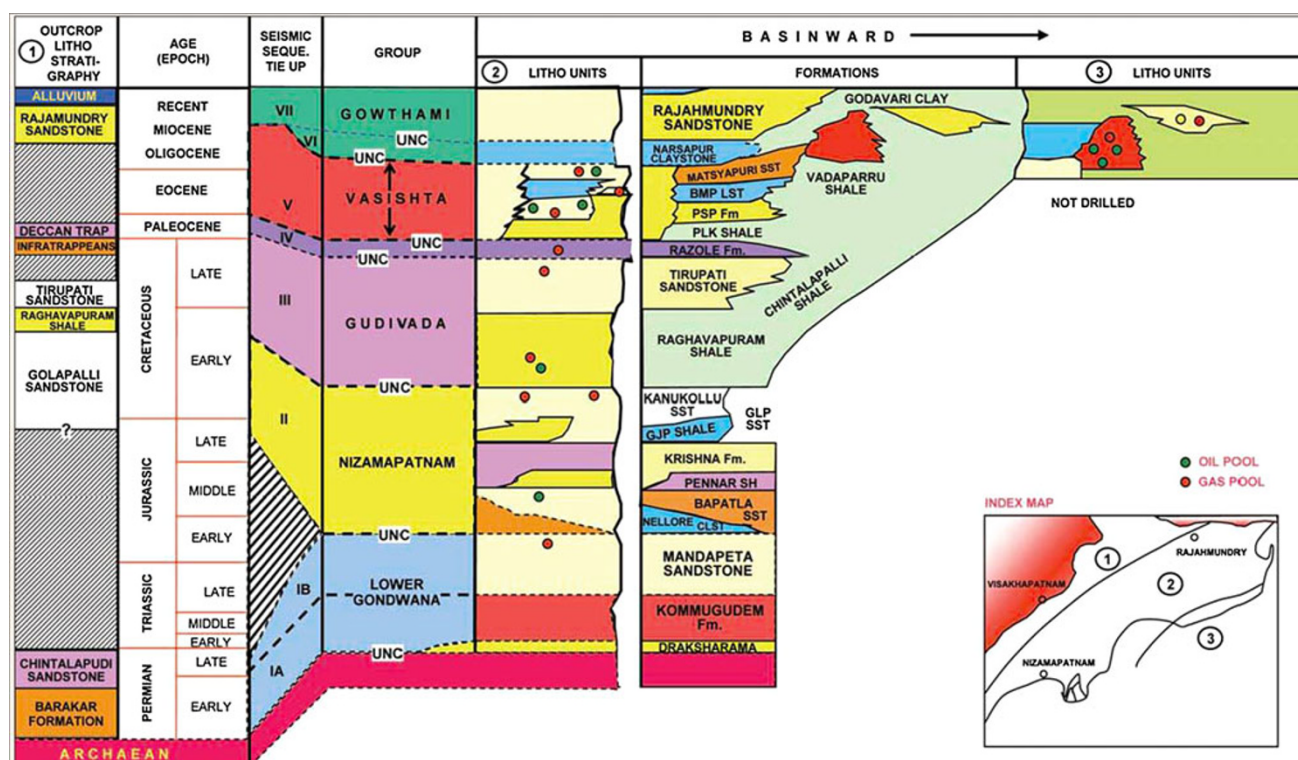
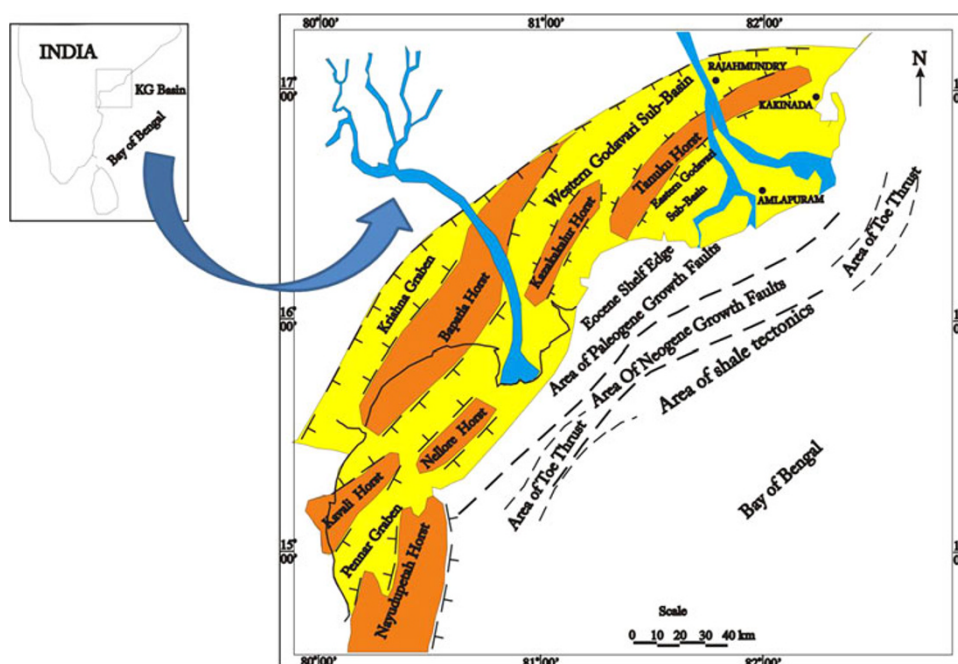


Fig. 3 General stratigraphy of the basin along with different oil and gas pools (Gupta 2006)

Results and discussions

Depth ranges of well bore ranges from 2,300 to 5,100 m covering the Early Cretaceous, Paleocene and Early Eocene. Figure 5 shows the relationship between hydrogen index (HI) and T_{max} values in these sediments from

GERMI #1, 2 and 3 in KG Basin. Thermal alteration pathways of organic matter Types-I, -II, and -III are indicated by dashed lines. Solid lines indicate approximate vitrinite reflectance values (not measured) that define the “oil window”. The geochemical results are plotted and also interpreted on hydrocarbon generation using hydrogen

Table 1 Measured rock-eval pyrolysis and additional derived parameters

Depth	S_1	S_2	S_3	S_2/S_3	PI	$S_1 + S_2$	OI	T_{max}	TOC	HI	R_o		
											Caved population	Indigenous	Oxidized population
2,325	0.25	4.62	5.16	0.9	0.05	4.87	199.23	430	2.59	178.38	nd	0.5219	nd
2,420	0.19	2.8	2.21	1.27	0.06	2.99	134.76	431	1.64	170.73	nd	0.5342	nd
2,545	0.18	2.22	2.43	0.91	0.08	2.4	139.66	432	1.74	127.59	nd	0.5533	nd
2,672	0.06	0.03	0.78	0.04	0.67	0.09	268.97	–	0.29	10.34	nr	nr	nr
3,492	0.2	1.09	0.64	1.7	0.16	1.29	43.24	450	1.48	73.65	nd	0.9767	nd
3,502	0.25	0.81	1.19	0.68	0.24	1.06	97.54	453	1.22	66.39	nd	0.962	1.387
3,657	0.25	0.46	0.72	0.64	0.35	0.71	54.14	456	1.33	34.59	nd	0.968	nd
3,815	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	0.436	1.06	2.53
3,820	0.37	1.43	0.7	2.04	0.21	1.8	37.63	436	1.86	76.88	nd	nd	nd
3,885.5	0.27	0.88	0.78	1.13	0.23	1.15	58.21	395	1.34	65.67	nd	0.9669	1.325
3,890	0.37	1.48	0.97	1.53	0.2	1.85	56.73	430	1.71	86.55	nd	1.06	nd
3,945	0.15	0.35	0.81	0.43	0.3	0.5	45	365	1.8	19.44	nd	1	1.5175
4,015	0.19	0.2	0.64	0.31	0.49	0.39	60.95	417	1.05	19.05	nd	1.0833	1.3925
4,070	0.22	0.39	0.6	0.65	0.36	0.61	61.22	379	0.98	39.8	nd	1.0367	1.6867
4,088	0.15	0.3	0.34	0.88	0.33	0.45	53.13	352	0.64	46.88	nd	1.11	1.5471
4,130	0.16	0.16	0.48	0.33	0.5	0.32	63.16	360	0.76	21.05	nd	1.0425	1.36
4,195	0.23	0.28	0.27	1.04	0.45	0.51	15.25	362	1.77	15.82	nd	0.9967	nd
4,200.5	0.19	0.27	0.15	1.8	0.41	0.46	24.19	395	0.62	43.55	nd	1.1375	1.275
4,220	0.31	0.33	0.33	1	0.48	0.64	11.46	458	2.88	11.46	nd	nd	1.47
4,250	0.57	0.63	0.28	2.25	0.48	1.2	21.54	366	1.3	48.46	nd	1.1725	1.5317
4,320	0.29	0.69	0.29	2.38	0.3	0.98	16.86	366	1.72	40.12	1.03	1.1743	nd
4,380	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	1.025	1.1618	nd
4,495	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	1.034	1.1984	nd
4,630	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	1.0767	1.1956	1.4975
4,740	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	1.0325	1.23	1.6025
4,795	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	0.9833	1.1567	nd
4,900	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	nd	nd	nd
4,970	nr	nr	nr	nr	nr	nr	nr	nr	nr	nr	0.3981	nd	nd
2,385	3.44	11.2	4.32	2.59	0.24	14.64	91.72	428	4.71	237.79	nr	nr	nr
2,405	2.8	10	7.3	1.37	0.22	12.8	119.87	431	6.09	164.2	nr	nr	nr
2,769	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd	nr	nr	nr
2,835	2.36	3.19	1.9	1.68	0.43	5.55	263.89	370	0.72	443.06	nr	nr	nr
3,391	nd	nd	nd	nd	nd	nd	nd	nd	0.23	nd	nr	nr	nr
3,538.5	2.18	1.62	0.96	1.69	0.57	3.8	73.28	451	1.31	123.66	nr	nr	nr
4,244.5	18.92	2.92	0.72	4.06	0.87	21.84	76.6	436	0.94	310.64	nr	nr	nr
4,275.4	3.15	0.93	0.18	5.17	0.77	4.08	15.38	362	1.17	79.49	nr	nr	nr
4,278	31.12	2.58	0.41	6.29	0.92	33.7	48.81	433	0.84	307.14	nr	nr	nr
4,281.5	4.57	0.99	0.17	5.82	0.82	5.56	13.28	420	1.28	77.34	nr	nr	nr
4,474.5	24.6	1.45	0.38	3.82	0.94	26.05	49.35	429	0.77	188.31	nr	nr	nr
4,486.2	nd	nd	nd	nd	nd	nd	nd	nd	0.19	nd	nr	nr	nr
4,487	23.44	1.27	0.46	2.76	0.95	24.71	65.71	428	0.7	181.43	nr	nr	nr
4,488.9	0.9	0.47	0.06	7.83	0.66	1.37	13.04	360	0.46	102.17	nr	nr	nr
4,500.9	nd	nd	nd	nd	nd	nd	nd	nd	0.42	nd	nr	nr	nr
4,655.5	nd	nd	nd	nd	nd	nd	nd	nd	0.22	nd	nr	nr	nr
4,659.9	4.67	0.34	0.14	2.43	0.93	5.01	32.56	355	0.43	79.07	nr	nr	nr
4,663.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr

Table 1 continued

Depth	S_1	S_2	S_3	S_2/S_3	PI	$S_1 + S_2$	OI	T_{\max}	TOC	HI	R_o		
											Caved population	Indigenous	Oxidized population
4,742.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
4,879.9	nd	nd	nd	nd	nd	nd	nd	nd	0.15	nd	nr	nr	nr
4,889.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
4,906.8	nd	nd	nd	nd	nd	nd	nd	nd	0.23	nd	nr	nr	nr
4,928.6	nd	nd	nd	nd	nd	nd	nd	nd	0.06	nd	nr	nr	nr
4,987.5	21.52	0.57	0.26	2.19	0.97	22.09	18.84	385	1.38	41.3	nr	nr	nr
5,195	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
5,292	38.16	1.2	0.17	7.06	0.97	39.36	12.69	424	1.34	89.55	nr	nr	nr
5,310.9	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
5,333.3	6.01	0	24.64	0	1	6.01	1811.76	nd	1.36	0	nr	nr	nr
5,351.3	nd	nd	nd	nd	nd	nd	nd	nd	0.44	nd	nr	nr	nr
5,372.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
5,407	16.6	0.26	0.12	2.17	0.98	16.86	13.64	385	0.88	29.55	nr	nr	nr
5,437	29.24	3.38	0.48	7.04	0.9	32.62	40	431	1.2	281.67	nr	nr	nr
5,447.5	nd	nd	nd	nd	nd	nd	nd	nd	0.1	nd	nr	nr	nr
5,508.5	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nr	nr	nr
5,628	17.8	0.61	1.32	0.46	0.97	18.41	118.92	425	1.11	54.96	nr	nr	nr
5,712.5	29.6	8.8	0.2	44	0.77	38.4	0.47	429	42.35	20.78	nr	nr	nr
5,717.5	25.2	3.25	0.28	11.61	0.89	28.45	7.55	385	3.71	87.6	nr	nr	nr
4,796.7	0.91	0.86	0.18	4.78	0.51	1.77	50.28	358	0.36	240.22	nr	nr	nr
4,790.5	0.31	0.24	0.14	1.71	0.57	0.55	28.69	347	0.49	49.18	nr	nr	nr
5,005.6	9.3	0.75	0.44	1.7	0.93	10.05	139.68	422	0.32	238.1	nr	nr	nr

Depth in mTVD unless and until mentioned otherwise; S_1 , S_2 , S_3 in mg HC/g rock; T_{\max} in °C; TOC in wt%; R_o in %

PI production index, OI oxygen index in mg HC/g organic carbon, HI hydrogen index in mg HC/g organic carbon, nr not recorded, nd not detected

Index as a function of temp, oxygen index, TOC, etc. Plotting T_{\max} versus HI shows the different maturation paths of different kerogen types (Fig. 5). T_{\max} values correlate directly with vitrinite reflectance values. The type and maturity of organic matter in petroleum source rocks have been characterized from rock-eval pyrolysis data (Fig. 6). Geochemical parameters including HI [hydrogen index, $(S_2/\text{TOC}) \times 100$], OI [oxygen index, $(S_3/\text{TOC}) \times 100$] and PI [production index, $S_1/(S_1 + S_2)$] are calculated. S_1 versus TOC plot gives a clear indication of the indigenous hydrocarbons and non-indigenous hydrocarbons (Fig. 7). Pyrolysis experiments were repeated for some samples at early sample weight to ensure that the rock-eval/TOC detector was not overloaded by generated hydrocarbons during the original runs (Ibrahimbas and Riediger 2002).

The analytical procedure, discussion and details of rock-eval pyrolysis parameters are available in Peters (1986) and Snowdon et al. (1998). Table 2 provides an interpretive guidelines based on S_2 values from rock-eval pyrolysis. Accordingly, the present study objectives are aimed to

evaluate the hydrocarbon source potential from the available core sample data and to study the thermal maturity of the geological sequence in parts of KG basin.

Source facies and TOC

Geochemical data reveal that interval 2,325–2,420 m (Early Eocene) TOC contents recorded are good to very good (1.64–2.59 wt %). Rock-eval pyrolysis data reveal moderate potential yields ($S_1 + S_2 = 2.99$ –4.87 mg HC/g rock). Figure 9 indicates a fair hydrocarbon source potential. Hydrogen indices were recorded (171–178) implying the presence of predominantly humic gas-prone kerogen (Type-III). Rock-eval pyrolysis reveals an average potential yield ($S_1 + S_2 = 1.09$ mg HC/g rock) and a low hydrogen index (=128 mg HC/g organic carbon) (Figs. 6, 8). The data suggest the sample has fair hydrocarbon source potential and contain predominantly gas-prone kerogen and has been cross-checked with well-testing reports (Kaawache and Mahapatra 2005). Visual kerogen composition data confirm the presence of predominantly of

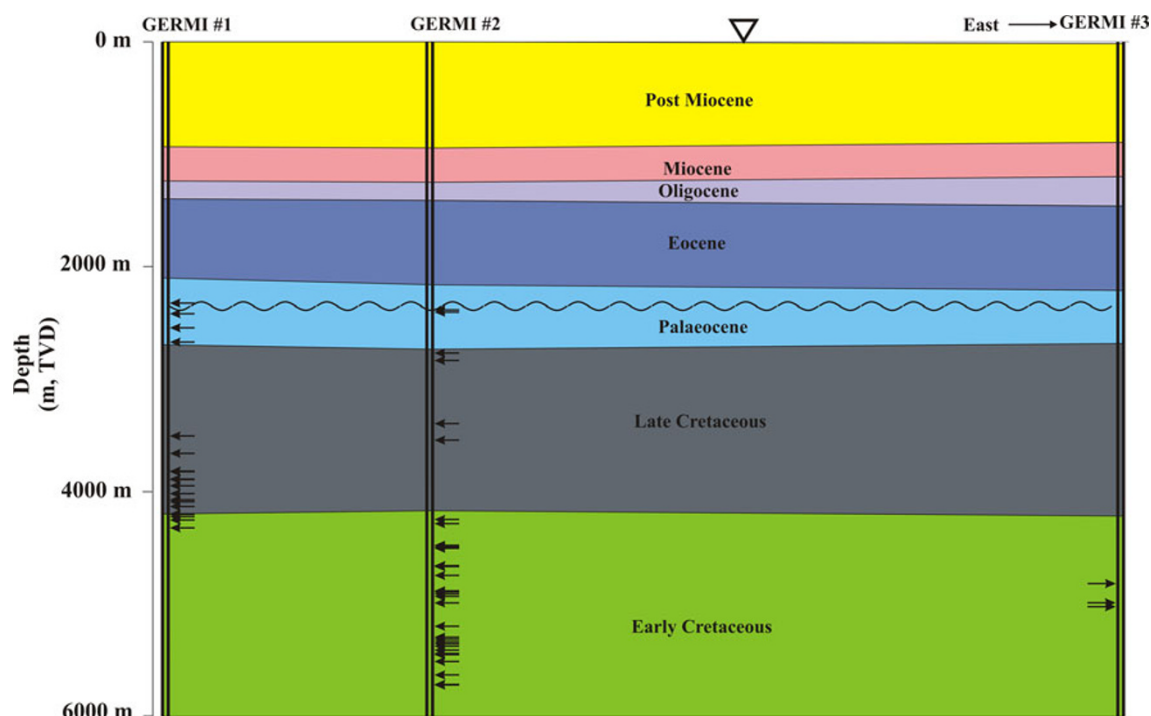


Fig. 4 Stratigraphy and lithology depth profile for well bores (GERMI #1, GERMI #2 and GERMI #3). Arrows indicate the sample locations

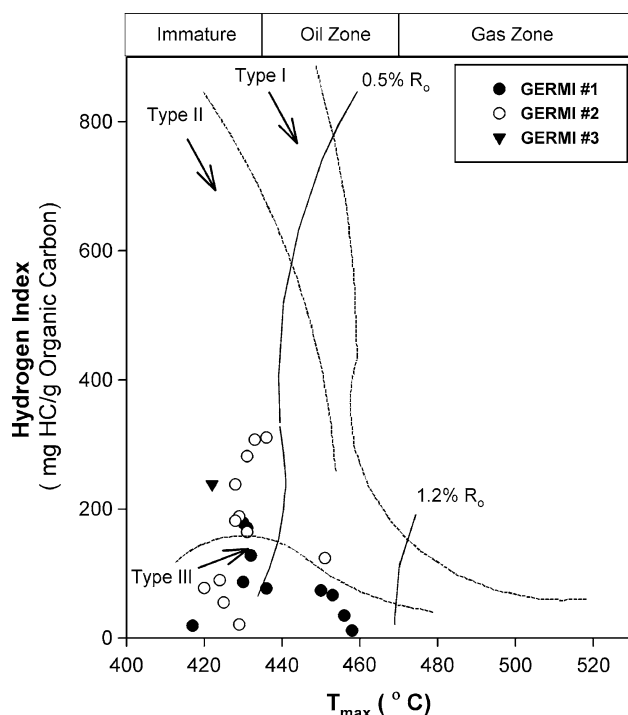


Fig. 5 Cross plot of rock-eval T_{max} versus hydrogen index (HI) data showing the range in thermal maturity as well as hydrocarbon generative (kerogen) types of samples, indicating immature to mature type-III kerogen from GERMI #1 and GERMI #2 while immature samples from GERMI #3

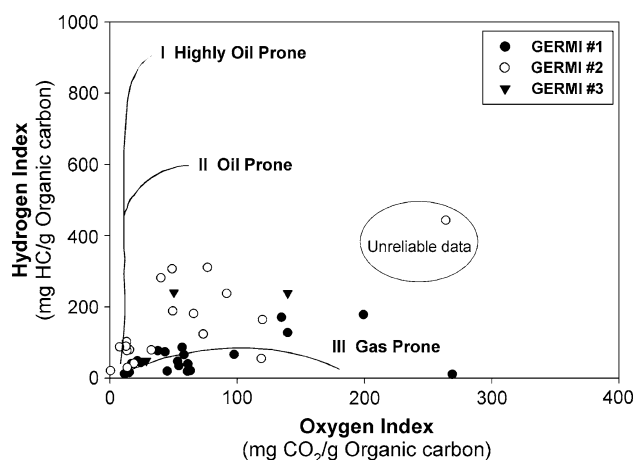


Fig. 6 HI versus OI plots on the modified Van Krevelen diagram of samples, indicating type-III gas-prone samples of all the borings

non-fluorescent kerogen (58 %) and vitrinite particles/Type-III kerogens (30 %) (Fig. 6).

Hydrogen indices (10–87 mg HC/g organic carbon) suggest the presence of gas-prone kerogen (Type-III). This is also confirmed by visual kerogen typing analysis, which was performed on all samples interval 4,070–5,050 m (Early Cretaceous) comprise mainly medium dark grey to olive grey claystones and medium dark grey to dark grey shales. TOC contents for these samples range from 0.20 to

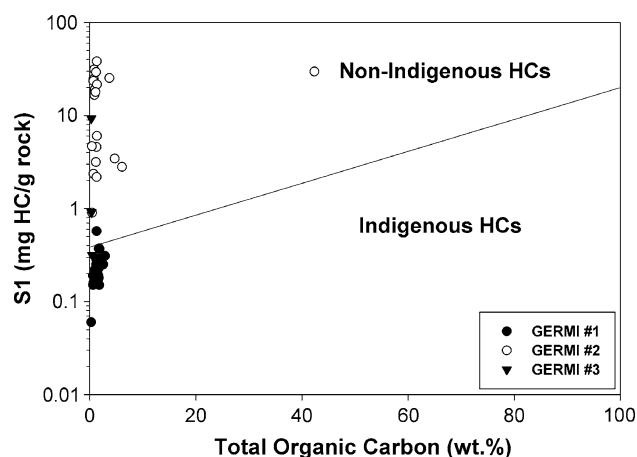


Fig. 7 S_1 versus TOC plots of samples indicating indigenous hydrocarbons of GERMI #1 and non-indigenous hydrocarbons of GERMI #2 and GERMI #3, except one sample (adapted from Hunt 1995)

Table 2 Standard criteria for rating potential source rocks based on S_2 values after Ibrahimbas and Riediger 2002

Rating	S_2 (mg HC/g rock)
Poor	<2.00
Fair	2.00–5.00
Good	>5.00

2.88 wt%. Rock-eval pyrolysis analysis reveal low to moderate hydrogen indices (ranging from 11 to 185 mg HC/g organic carbon) implying the presence of predominantly gas-prone kerogen (Type-III) (Fig. 8). Visual kerogen typing analysis performed on these samples show the abundance of non-fluorescent amorphous debris (10–73 %), with secondary amounts of vitrinite particles (7–56 %). Toward the base the kerogen are dominated by vitrinite, semifusinite and inertinite maceral.

In GERMI #2 the conventional core samples from the depth range of 2,385–5,718 m are taken for TOC determination. Overall, the samples contain relatively low TOC (<2 %) indicative of poor to moderate organic richness. However, the low TOC contents suggest the section has little potential for hydrocarbon generation (Fig. 8). The rock-eval pyrolysis indicates the potential source to be gas prone at best. $S_1 + S_2$ versus TOC plots of samples indicating fair to good source rock potential of samples from GERMI #2 (Fig. 9). Based on T_{max} values between 370 and 431 °C, the Late Claystone section appears to be immature to marginally mature (Fig. 9). The early value of T_{max} 370 °C could be due to the presence of free hydrocarbons. Hydrogen indices (HI) (~164 to 443 mg HC/g organic carbon) and suggest that the samples are oil prone (Fig. 5). Between 3,538.5 and 5,717.5 m the TOC value ranges from 0.1 % (5,447.5 m) to 3.71 % (5,717.5 m), with most

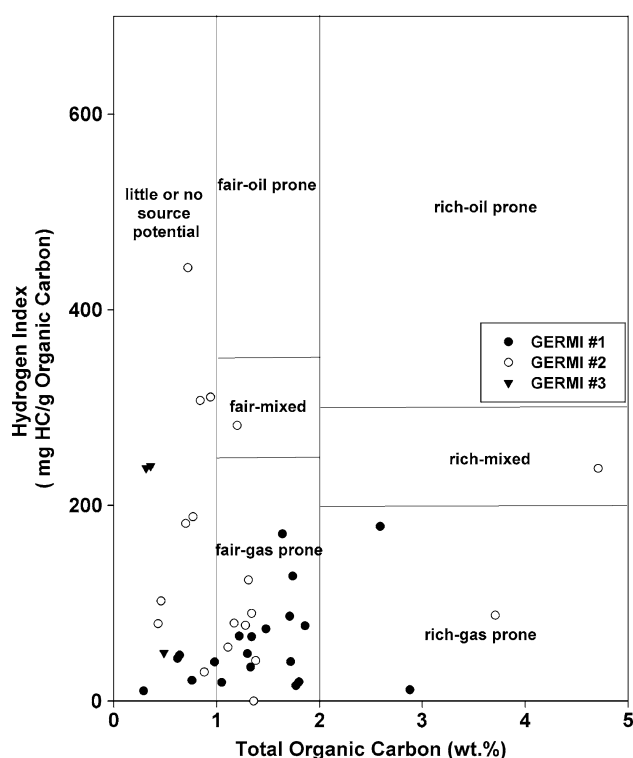


Fig. 8 HI versus TOC plots of samples indicating fair to rich gas potential of samples from GERMI #1 and GERMI #2 while little or no potential from GERMI #3

values between 0.4 and 1.5 % (fair to good) except some higher TOC values at 5,712.5 m, which is because of presence of coal. S_1 values ranges from 2.18 to 29.6 mg HC/g rock characterizing excellent levels of free hydrocarbons, except 0.9 mg/g value at 4,488.9 m. Hydrocarbon generating potentials are poor to moderate (S_2 values between 0.26 and 3.38 mg HC/g rock) and T_{max} values between around 420 and 450 °C reflect immaturity to maturity (Fig. 9). Low T_{max} values below 400 °C are likely to be artifact, caused by T_{max} suppression due to the presence of considerable level of free hydrocarbons (S_1). HI vary between 30 mg HC/g organic carbon (gas) and 311 (gas and oil), with most values indicating a more gas-prone character of the source sediments than the oil. Interpreted hydrocarbons are matching with well-testing reports (Asianto and Losier 2007; Asianto and Rosier 2007).

The number of samples from GERMI #3 are very limited (Fig. 4) but still those sample were showing HI in the range of 32–50 mg HC/g organic carbon with most value indicating the gas-prone character of the sediments. The hydrocarbon generation potential varies from poor to moderate (Fig. 6). The obtained geochemical results have been confirmed from well-testing reports (MacLennan et al. 2007; Jong and Pelsner 2007). Due to side tracking borehole GERMI #3 has got three samples for which geochemical analysis has been carried out.

Fig. 9 $S_1 + S_2$ versus TOC plots of samples indicating fair to good source rock potential of samples from GERMI #1 and GERMI #2 while poor potential from GERMI #3

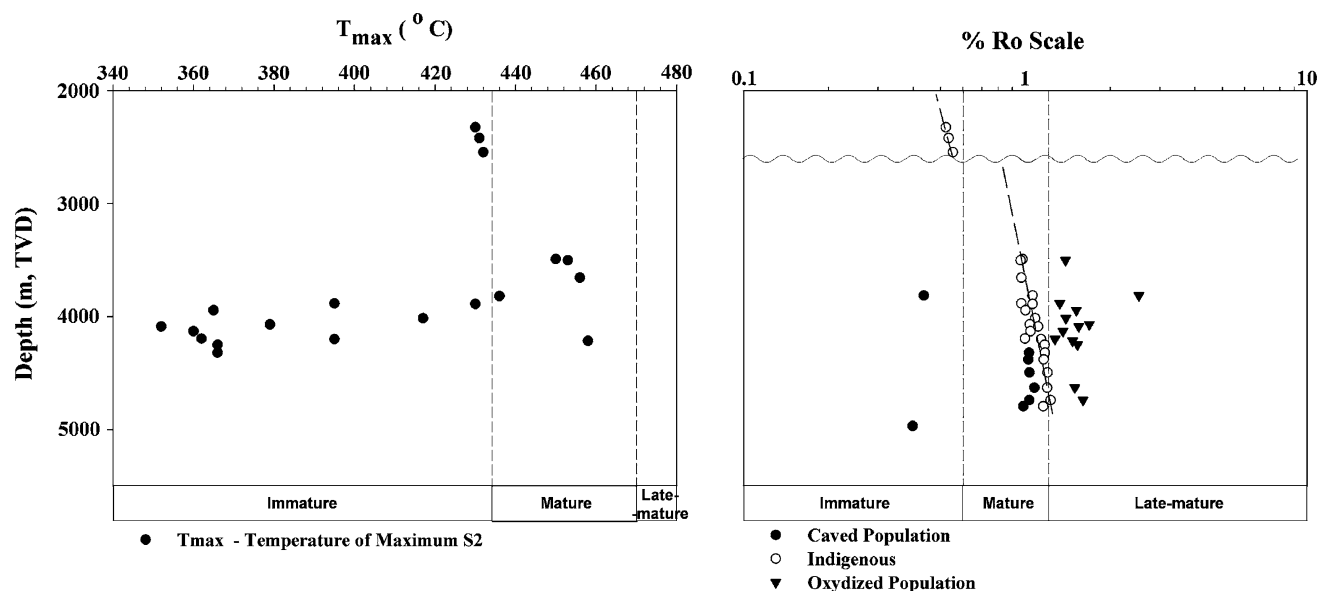
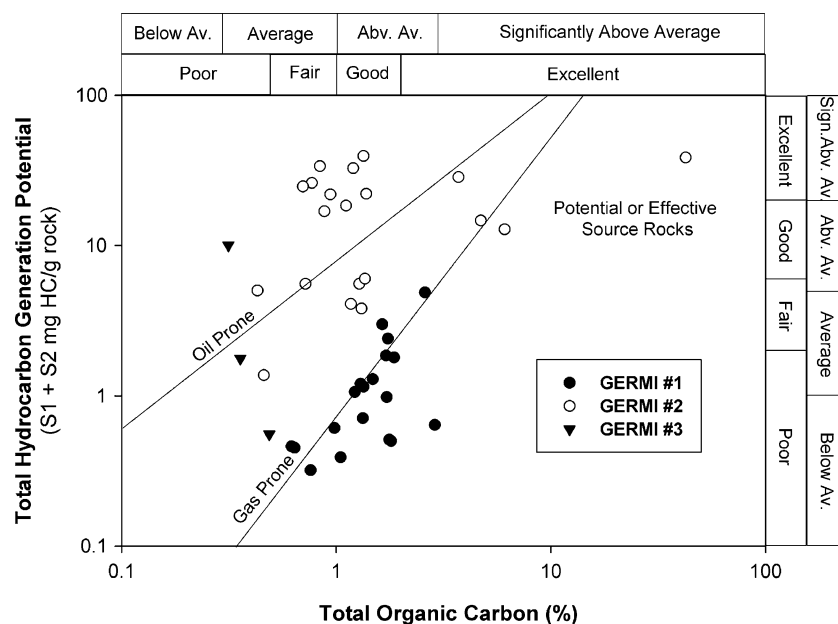


Fig. 10 T_{max} and R_o depth profile for GERMI #1 indicating break in maturity profile due to significant erosion during the uplifted prior to deposition of overlying formations. Note the matured indigenous core samples

Maturity evaluation, vitrinite reflectivity analysis

In GERMI #1 a total of 30 samples throughout the interval 2,325–5,050 m were submitted for vitrinite reflectivity analysis (polished whole rock). The results are generally fair to good based on variably low to abundant recoveries of vitrinite particles. Samples from depth 2,672, 4,900, 4,995, 5,010 and 5,050 m were found to be barren of indigenous vitrinite particles (Asianto and Losier 2007; Asianto and Rosier 2007). Recorded mean vitrinite reflectivity values range from 0.52 % R_o (at 2,325 m) to 0.55 % R_o (at 2,545 m) (Fig. 10). The interpreted vitrinite reflectivity profile shows that the section

is marginally mature for oil generation. Below 3,492 m there is a rapid increase in vitrinite reflectivity values from late mature to post mature. The R_o values increase uniformly from 0.98 % R_o (at 3,492 m) to 1.16 % R_o (at 4,795 m) indicating that the section is late mature for oil generation (Fig. 10). As mentioned earlier, sample 2,672 m was found barren of indigenous vitrinite particles. It is noted however, that spore colouration analysis on this sample (discussed below) confirms it is marginal mature for oil generation. Hence, the rapid increase in vitrinite reflectivity within the interval 2,673–3,492 m is thought to be associated with a significant unconformity which occurs at depth c. 2,675 m.

The argillaceous sediments analyzed throughout the sequence (interval 2,325–5,050 m, Early Eocene to Early Cretaceous) display variably very low to good organic richness (TOC in the range of 0.20–2.88 wt%). These sediments are considered to have poor to fair hydrocarbon source potential ($S_1 + S_2 = 0.09$ –4.87 mg HC/g rock) and contain mainly gas-prone kerogen based on low to moderate HI values (11–185 mg HC/g organic carbon). Visual kerogen analysis on these samples confirms the presence of predominantly gas-prone kerogen (90–99 %). The gas-prone kerogen consists of vitrinite maceral and non-fluorescent amorphous debris. The non-fluorescent amorphous material is possibly sapropelic debris which has been affected by thermal maturity.

Conclusions

Based on the detailed analysis of the rock samples from three different deep offshore wells, the following major conclusion can be drawn.

- A break in maturity profile observed in GERMI #1 suggests that there is a significant amount of erosion. This area is known to be tectonically active; it can be interpreted that the erosion might have taken place during the uplifted period prior to deposition of overlying formation. Additionally, reported high heat flow values have been contributed significantly for the maturity levels. From the extrapolation of R_o profile to the surface indicates that the reaction might be at a much deeper depth of burial and have experienced high temperature. There could be alternate interpretation of the break in maturity profile of the well. However, additional data like FAMM (fluorescence alteration of multiple macerals), VIRF (vitrinite inertinite reflectance and fluorescence) and burial history modeling are required.
- S_1 versus TOC plot indicates possible indigenous hydrocarbons from borehole GERMI #1 while non-indigenous hydrocarbons from boreholes GERMI #2 and GERMI #3.
- Different rock-eval pyrolysis parameters are suggestive of immature to early mature gas-prone shales from borehole GERMI #1 while early mature to mature oil and gas-prone shales from borehole GERMI #2. Limited samples from GERMI #3 are indicative of immature shales. Well-testing analysis also supports the type of hydrocarbons interpreted.

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